Lagrangian Transport Signatures in Models and Observations

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LONG-TERM GOALS

A common thread running through much of our research is a description of the ocean flows from a Lagrangian perspective. We aim to identify and study the properties characterizing the transport patterns in the ocean. These are of importance for a wide range of applications, from the dispersion patterns of drifting sensors to predicting the distribution of chemicals in the ocean and even to search and rescue missions. Since relevant observations are sparse and exceedingly expensive to collect, much of the information about Lagrangian dynamics is derived from ocean models. In this project, we evaluate how well the Lagrangian signatures in the model fields compare with observations.

OBJECTIVES

Within the overall objective of identifying and comparing Lagrangian transport signatures in models and observations, we are primarily interested in two aspects of the problem: (1) what Lagrangian features tell us about mixing processes across eddy boundaries and fronts; and (2) the predictability of these features and the underlying transport patterns. Building on our work from FY10 developing methods for identifying and tracking eddies, in FY11 we have quantified the fluid exchange between one particular eddy, the Loop Current Ring Fourchon in early 1988, and its environment from model data over the course of the eddy's life. We have also been able to make much progress on the second aspect of the problem, due in great part to the wealth of observations and model data that became available in connection with the clean-up efforts of the Deepwater Horizon oil spill in the Gulf of Mexico in the spring of 2010. In that context, we pursued the concrete objective of evaluating model forecasts of the movement of the oil slick on the surface.

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APPROACH

1. Lagrangian transport signatures and mixing: The case of Fourchon

In FY10, we investigated how best to define the extent of an eddy. This is crucial for determining fluid exchange rates and mechanisms, yet no one definition is generally used and accepted in the community. The most intuitively reasonable results were obtained by considering the following two algorithms: (a) the largest closed sea surface height (SSH) contour exceeding a minimum value; and (b) the mean of the largest spiraling instantaneous streamlines started on radials at 1˚ intervals subject to a maximum endpoint separation and a maximum change in area from that contained in the next smaller streamline. The latter algorithm requires significantly more computation, so that algorithm (a) has been adopted for most of the further inquiries.

Either algorithm is readily extended into the water column to account for the baroclinic structure of ocean eddies, by replacing geopotential height anomaly contours for SSH contours and computing instantaneous streamlines at lower levels. However, differences between the two algorithms tend to be larger at depth than at the surface. Moreover, the model is most strongly constrained at the surface, where most observations are available for assimilation and validation. Thus, the surface signature of the eddies is expected to be more accurate.

For this reason, we started our analysis with the two-dimensional dynamical evolution of the near-surface expression of the eddy Fourchon over the period from 19 February to 25 July 1998. Fourchon is a typical Loop Current Ring (LCR) in the Gulf of Mexico. The processes responsible for its breakup have previously been studied in *Lipphardt et al., 2008*. Here we consider its evolution over a longer time period. Specifically, we consider the changes in the surface layer areal extent and the mean and total vorticity of the eddy. By comparing the Eulerian evolution of the eddy boundary (i.e. the boundary as identified by the chosen algorithm described above) to its Lagrangian counterpart (i.e. the boundary as moved by the fluid flow), it is possible to quantify the fluid exchange between the eddy and its surroundings. We have chosen daily time steps for this analysis, but also considered the cumulative picture.

The analysis is based on the University of Colorado implementation of the Princeton Ocean Model, CUPOM, for the Gulf of Mexico. CUPOM has 1/12˚ resolution. It uses climatological open boundary and initial conditions. Sea surface height and temperature from satellites are assimilated.

2. Lagrangian predictability: The Deepwater Horizon oil spill

While the historic oil spill following the explosion of the Deepwater Horizon (DH) drilling rig in April 2010 brought with it many tragic consequences, it also provided a unique opportunity for physical oceanographers to apply Lagrangian prediction tools to create oil drift forecasts with immediate relevance to large numbers of people. During the crisis, evaluating individual forecasts took a backseat to the immediate need to look yet further ahead to the next day. Afterwards, with less pressing needs for immediate answers, we were able to develop assessment metrics for oil spill forecasts and apply them to the observations and model output from the DH spill.

Observed surface oil slick locations were drawn from two independent sources: the University of South Florida's Optical Oceanography Laboratory's image gallery (hereafter USF, http://optics.marine.usf.edu/events/GOM_rigfire), and the repository of estimates from Roffer's Ocean

Fishing Forecasting, Inc. (ROFFS™, http://www.roffs.com/deepwaterhorizon.html). A Gulf of Mexico regional, nested implementation of HYCOM (GOM-HYCOM), as run and maintained at NRL, Stennis, was used for state-of-the-art model results. This model has 1/25˚ resolution. Open boundary and initial conditions are drawn from an Atlantic 1/12˚ HYCOM implementation. Standard NCODA data assimilation is performed daily at midnight. For the present analysis, hindcast data was used whenever available for an upper bound on the model's predictive skill.

To predict oil slick movement, model oil particles were initialized along the observed boundary and advected with the flow. Unlike some previously published work, a stochastic diffusion term was not applied here, since it clouds physical intuition of the modeled processes and is so highly tunable that a particular implementation is hard to justify a priori. The resulting forecast was then compared to available observations, both qualitatively and quantitatively. For the latter, we developed two complementary metrics specifically for surfaces, rather than individual trajectories. These are: (1) the percent of the forecast plume that lies within the observed outline; and (2) the percent of the observed oiled area captured by the forecast.

In addition to the straight-forward advection by ocean flows, the role of additional forcing by winds was studied. Also, the effect of a simple model for continuous oil leakage was evaluated. Unfortunately, little data is available for the oil release rate, nor is the process of oil rising in the water column under pressure well understood. Consequently, we resorted to a simplistic model of pulses of additional oil reaching the surface with perfectly circular shapes every three hours. Various values for the circle's radius were explored.

Finally, we investigated how Lagrangian coherent structures could be used in the context of oil spill forecast and mitigation. For this purpose, we computed the Finite Time Lyapunov Exponents (FTLEs) from the model velocity fields and examined their structures relative to the observed and modeled oil motion.

WORK COMPLETED

In FY11, we followed two lines of inquiry: (1) Lagrangian aspects of mixing across eddy boundaries; and (2) Lagrangian forecasts for oil spill evolution. More specifically, under the first theme, we

- implemented and compared two eddy boundary detection algorithms at depth based on geopotential height contours and based on nearly closed instantaneous streamlines;
- studied the structure of eddies at depth;
- quantified area and vorticity changes for the LCR Fourchon over the course of its life (157 days); and
- quantified the fluid exchange at the surface between Fourchon and its environment.

Under the second theme, we

- generated oil spill forecasts based on GOM-HYCOM and initialized with observations of the surface slick from two separate sources;

- developed two complementary metrics to evaluate the quality of oil spill surface movement forecasts against observations;
- evaluated the following potential error sources: windage effects, unspecified continuous leakage, and initialization uncertainty; and
- investigated the usefulness of Lagrangian coherent structures in the context of oil spill forcasts.

RESULTS

1. Lagrangian transport signatures and mixing: The case of Fourchon
Based on an analysis of eddy surface signatures, two algorithms for defining eddy boundaries were determined to yield similarly reasonable results, that based on SSH contours and that based on instantaneous streamlines. These algorithms were then extended into the water column to discover the three-dimensional structure of an eddy. Figure 1 compares the two results for the LCR Fourchon on 12 May 1998. (The day was chosen for the mostly circular shape of the eddy.) The shapes display differences but are overall similar. While the cross-sections vary with depth, by either definition, it is clear that there is no consistent narrowing. Instead, Fourchon is more cylindrical than conical. Our analysis also showed that a typical depth for Fourchon is 400 m.

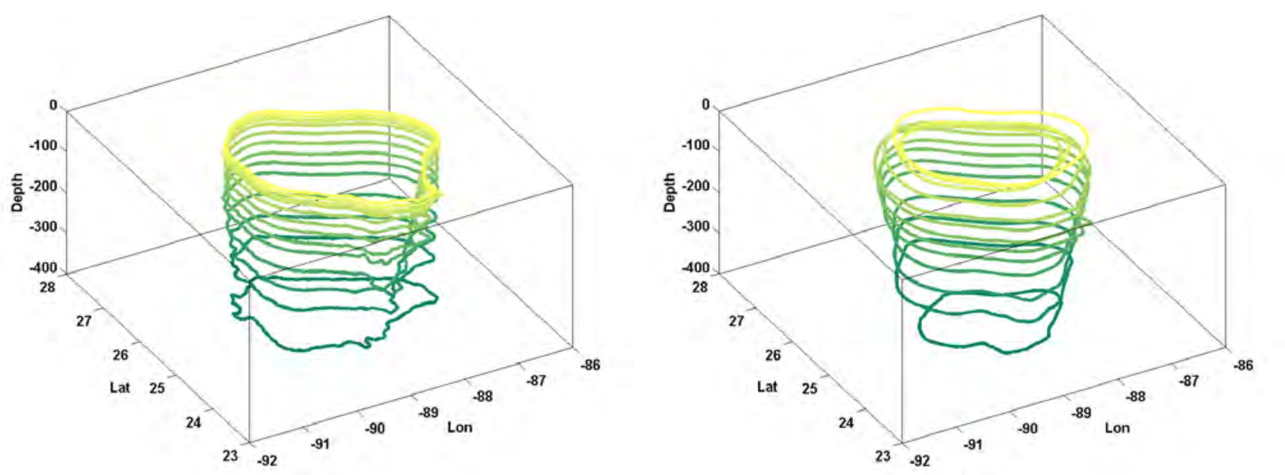

Figure 1: 3D structure of the LCR Fourchon as seen in CUPOM on 12 May 1998 based on two distinct algorithms for detecting the eddy boundary, based on geopotential contours (left) and instantaneous streamlines (right). The eddy cross-sections change shape somewhat with depth, but overall the eddy is seen to narrow very little and end abruptly at a depth of about 400 m.

A full 3D analysis of eddy evolution is currently being undertaken and will be reported on in FY12. Here we present results from the surface layer. Two key characteristics of eddies are their size and their vorticity. The former determines the extent of an eddy's impact on the flow field, while the latter is a measure of the eddy's strength. The left panel of Figure 2 shows time series of mean vorticity and area. Both quantities show sizable variability, and they appear to track each other to some extent, so that the strongest mean vorticity (largest negative value) is found when the eddy is smallest. This counterintuitive behavior suggests that total vorticity is the more meaningful measure of eddy strength

(right panel of Figure 2). Significant variability is exhibited in this time series as well. For the middle third of the eddy's life (about 40 days) its total vorticity is more or less constant. Then, starting around day 100, it increases toward zero fairly constantly, demonstrating that the vorticity loss preceded the areal decrease (starting around day 140) and likely caused the ultimate demise of Fourchon.

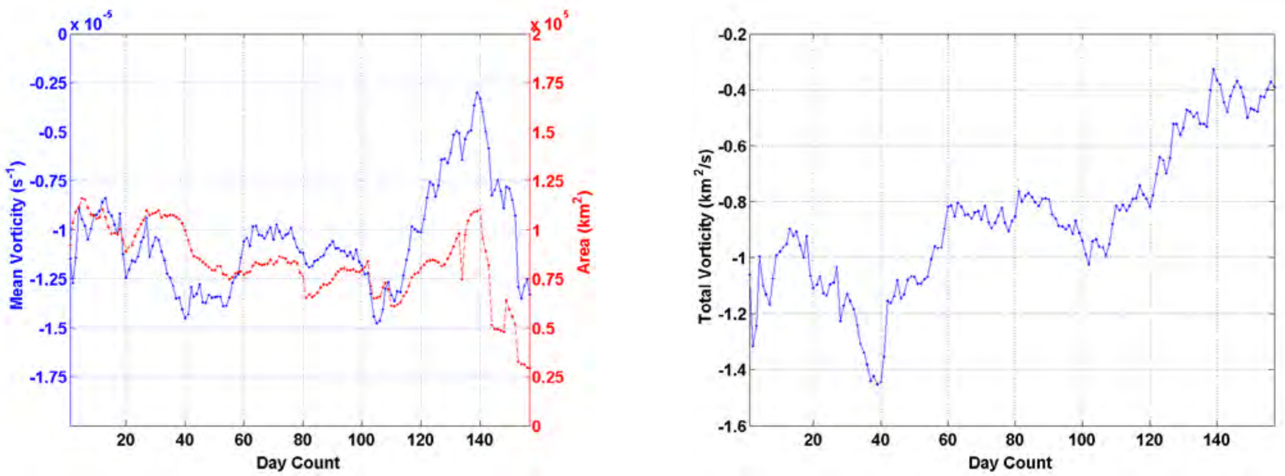

Figure 2: (Left) Time series of mean vorticity (blue) and area (red) of the surface expression of LCR Fourchon, derived from SSH contours in CUPOM, from 19 February 1998 to 25 July 1998. Note that both time series are variable with no clear trend. While the areal extent decreases sharply over the last two weeks, the mean vorticity also decreases (becomes more negative), suggesting counter-intuitively a strengthening shortly before the eddy's demise. (Right) Time series of total vorticity for the same time period. The eddy's total vorticity stays relatively constant for a long period of time (~ 40 days) in the middle of its life; then it steadily decreases to about half of the earlier value and stays roughly constant again during the last two weeks. This indicates that the strengthening suggested by the mean vorticity (left) is a mirage, reflecting only the shrinking of the eddy.

Eddy boundaries have traditionally been thought of as material curves, with no or little fluid exchange across them. Previous studies (e.g. *Lipphardt et al., 2008*) have shown that, on the contrary, exchanges between eddies and their environment play a crucial role in the breakup of LCRs. In fact, fluid fluxes are substantial throughout the eddy's lifetime. Figure 3 shows time series of daily fluxes and cumulative fluxes, as determined based on SSH contoured boundaries. The time series for daily fluxes into and out of Fourchon, as well as the net flux, (top panel) are noisy but without a significant trend. The cumulative net flux also displays some variability but remains overall near 0. Nonetheless, the cumulative inbound flux (and outbound flux, of course) is large. In fact, it corresponds to about ten times the average area of the eddy. Thus, rather than forming a consistent mass of water that translates west in the Gulf of Mexico with the LCR, on average the water making up the eddy is exchanged ten times over the course of the 157 days that the eddy exists.

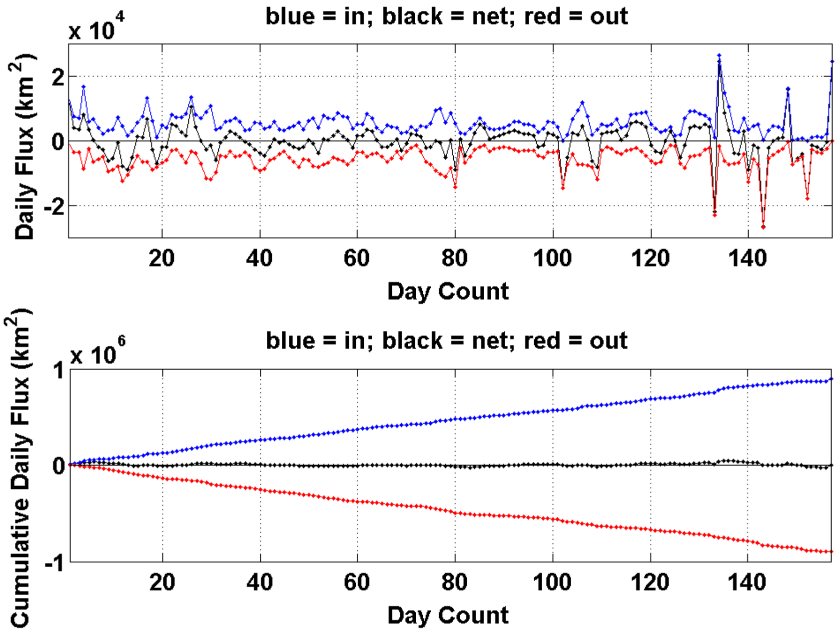

Figure 3: Fluid exchange between LCR Fourchon and its environment in CUPOM, from 19 February 1998 to 25 July 1998. Daily fluxes (top) are variable but without trend. The net cumulative flux (bottom) remains small, but the fluxes in and out of the eddy are substantial, adding up to about ten times its average area over the 157 days of its life.

2. Lagrangian predictability: The Deepwater Horizon oil spill

Predicting the motion of oil on the surface of the ocean is a challenging task. In the case of the Deepwater Horizon spill, additional complications arose due to an unknown flow rate and a source at depth with uncertain dynamics within the water column. The predictive skill of the state-of-the-art GOM-HYCOM was evaluated for two initialization dates and for two forecast periods each, chosen so that high quality observations were available for both start and end dates. An example of the results is shown in Figure 4.

The oil slick deforms according to the surface ocean flow. Both the observation and the predictions show clearly that the edge of the spill is drawn into the northern edges of the Loop Current. They also agree on the oil driven west along the coast, although this branch of the slick is enhanced in the model. The model moreover erroneously shows small amounts of oil moving northward along the coast.

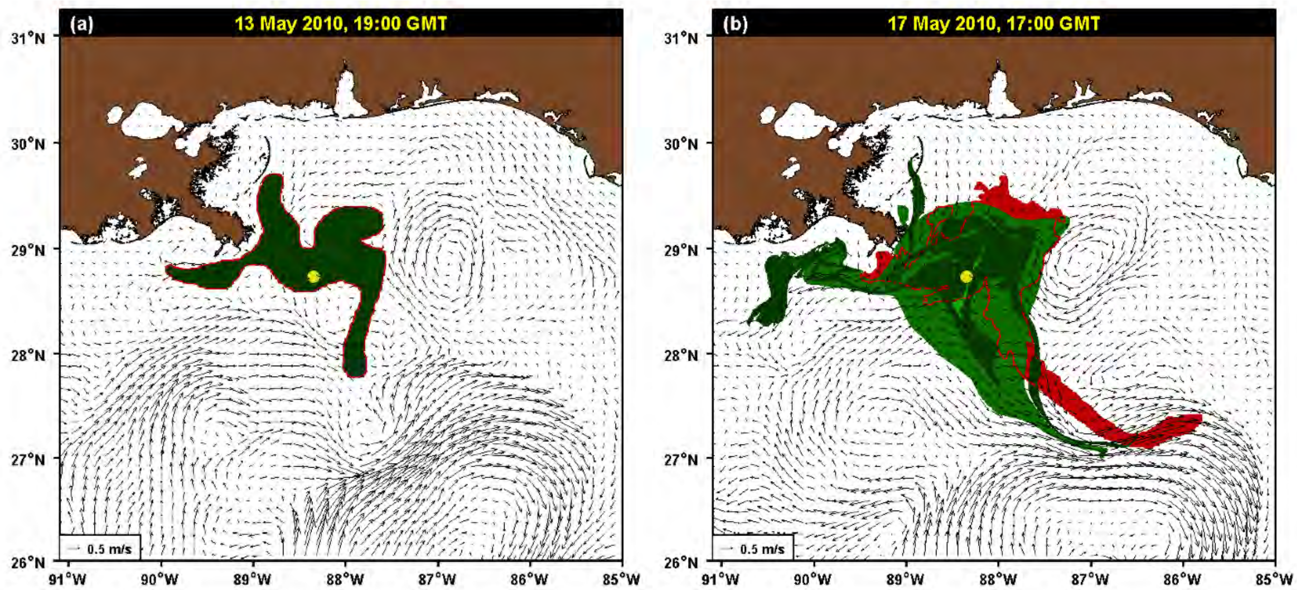

Figure 4: Deepwater Horizon oil spill forecast initialized with USF observation on 13 May 2010, 19:00 GMT, (left panel); on 17 May 2010, 17:00 GMT (right panel). The red indicates the USF observation. The dark green corresponds to the evolution of the initial oil. Light green shows additional oil from R = 15 km pulses; medium green shows additional oil from R = 80 km pulses. The yellow circle coincides with the oil well location. *(From Huntley et al., 2011.)*

We investigated to what extent the forecast errors can be reduced by allowing for continual oil spillage. The results are shown in Figure 4 (right panel) with the lighter shades of green, where different rates of replenishment were assumed for the two colors. The slower rate (three-hourly pulses with a radius of 15 km) has very little effect, while the faster rate (three-hourly pulses with a radius of 80 km) shows a much larger area covered in oil. All three forecasts display a generally similar deformation of the oil patch. In addition to the effect of the replenishment rate, the impact of allowing for windage (at 3% of the wind speed with no veering angle) was investigated. The wind was found to have little influence, although it leads to small displacements of the forecast and has a more noticeable effect near the coast (not shown). Initialization uncertainty proved to be important for this problem. Figure 5 illustrates this, showing two observational estimates of oil presence on 13 May 2010 (left panel) and the corresponding model forecasts (right panel). The ROFFS initialization leads to significantly less oil near the coastline, which is in accordance with both observations on 18 May 2010. The other main feature of oil being entrained into the Loop Current can be seen in either realization.

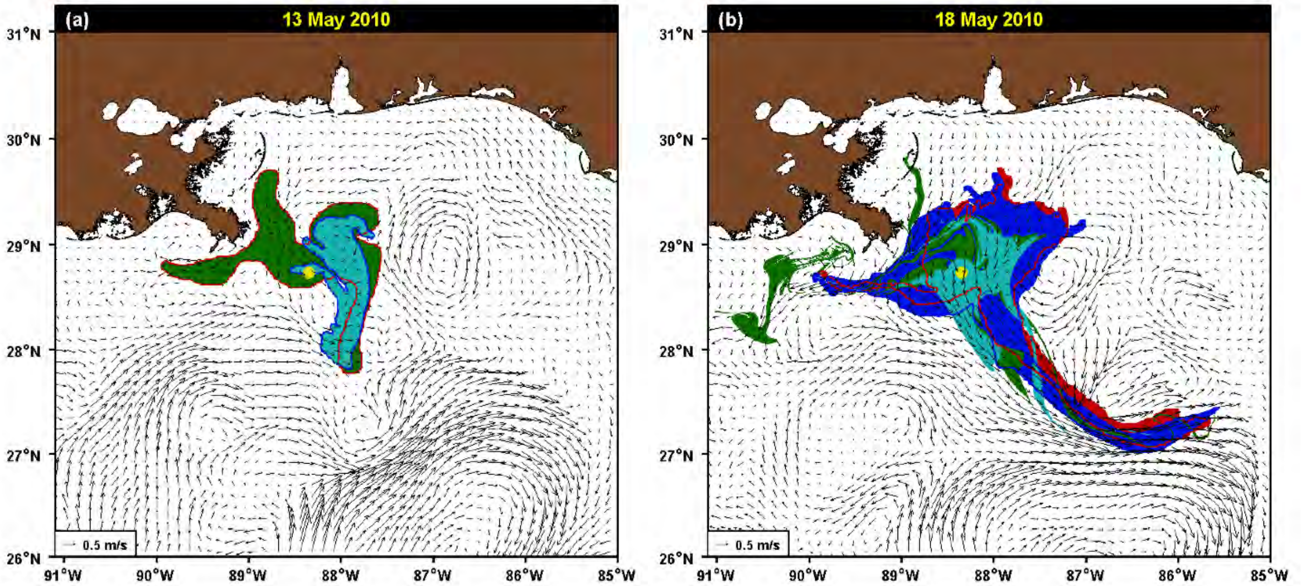

Figure 5: Comparison of Deepwater Horizon oil spill forecast initialized with USF observation (red/green) and with ROFFS observations (blue/cyan) on 13 May 2010 (left panel); on 18 May 2010 (right panel). Both forecasts were performed with additional oil added in R = 15 km pulses. Red and blue show the observations, while green and cyan display the model forecasts. The yellow circle coincides with the oil well location. *(From Huntley et al., 2011.)*

In order to quantify the match between observation and model prediction, we considered two metrics: (1) the percent of the forecast plume that lies within the observed outline; and (2) the percent of the observed oiled area captured by the forecast. Table 1 summarizes the results for the experiments. For no or small new supply, the second metric is consistently around 30 – 35 %, regardless of length of forecast (within the 2 to 5 day window studied) and whether or not wind forcing is included. A small continuous source leads to only small improvements, while a larger source gives significant gains in this metric, with values around twice as high or better. The trade-off is that the first metric is generally reduces, although not as severely.

In an attempt to identify areas of high uncertainty in the oil spill forecasts, Lagrangian coherent structures, in the form of FTLEs, were analyzed. Dynamical systems theory suggests that initializations near stable (or inflowing) manifolds – approximated by ridges in forward time FTLEs, shown in blue in Figure 6 – are particularly prone to error, since small displacements of these manifolds can lead to large differences in the forecasts. Such sensitivity can be seen in the areas highlighted by the two ovals on the left side. The two ovals on the right indicate areas where oil is initially near unstable (or outflowing) manifolds – approximated by ridges in backward time FTLEs, shown in red in Figure 6. These manifolds indicate primary stretching directions. Following the dynamic evolution of the manifold structure, it can be seen that indeed both the model forecast and the observation display movement along these red ridges, away from the hyperbolic regions at the crossings with blue ridges. While more work is needed to develop more precise methods for interpreting FTLE maps in this context, the present results demonstrate utility in identifying primary patterns of deformation and regions of forecast uncertainty, independent of initializations based on observations.

Table 1: Performance metrics for a variety of experiments forecasting the Deepwater Horizon oil spill with GOM-HYCOM. Observed area on the final forecast day is given in the rows with the dates.

	Area (in 1000 km^2)	**% fcst in obs**	**% obs in fcst**
6 May – 8 May 2010	28.5 (USF)		
No new supply	11.2	76	30
15-km new supply	11.7	76	31
15-km new supply + wind	12.8	77	35
80-km new supply	27.6	62	60
6 May – 10 May 2010	14.7 (USF)		
No new supply	10.6	32	23
15-km new supply	12.7	40	34
15-km new supply + wind	14.2	36	35
80-km new supply	32.8	36	81
13 May 2010 – 17 May 2010	20.0 (USF)		
No new supply	12.8	54	34
15-km new supply	13.2	54	35
15-km new supply + wind	11.7	50	29
80-km new supply	32.8	44	71
13 May 2010 – 18 May 2010	20.0 (USF)		
No new supply	11.9	52	31
15-km new supply	12.3	51	31
15-km new supply + wind	12.4	45	28
80-km new supply	35.0	43	75

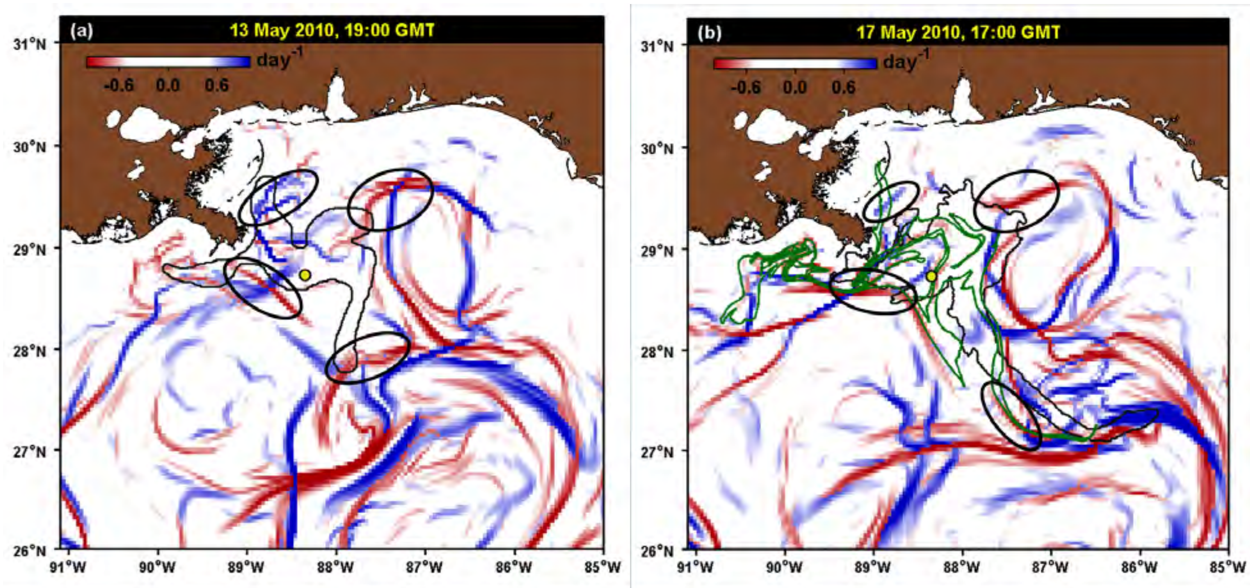

Figure 6: Maps of 3-day DLE on 13 May 2010, 19:00 GMT (left) and on 17 May 2010, 17:00 GMT (right). Forward-time calculations are shown in blue, and backward time calculations are shown in red. The dark grey outline shows the USF observed oil extent; the green outline shows the forecast initialized on 13 May 2010 with the USF observation (without replenishment). The yellow circle with black rim coincides with the oil well location. Black ovals identify regions discussed in the text. *(From Huntley et al., 2011.)*

IMPACT/APPLICATIONS

The estimation of fluxes between eddies and their environment is important for understanding mixing in the oceans. Since eddies are prominent flow features, thought to be largely responsible for heat transport, e.g., understanding their behavior has large-scale implications. The ability to evaluate oil spill forecasts quantitatively is crucial for improving oil spill response and preventive planning.

RELATED PROJECTS

This project is closely related to the following other ONR projects involving the same principal investigators:

N00014-11-1-0087: Dynamical systems theory in 4D geophysical fluid dynamics – This MURI program is concerned with moving Lagrangian analysis of general circulation models from two (horizontal) spatial dimensions to three full dimensions. While currently most calculations are restricted to individual layers of a model, this project will connect these and develop methods for understanding the 3D evolution of Lagrangian coherent structures.

N00014-09-1-0559: Assessing the Lagrangian predictive ability of Navy ocean models – This work aims to estimate uncertainty in ocean models by analyzing ensembles of model runs from operational Navy models.

N00173-08-1-G009: Prediction of evolving acoustic sensor arrays – This effort is focused on demonstrating how Lagrangian analysis of Navy ocean model predictions can be performed at a Navy operational center and how Lagrangian products can be delivered to fleet operators on scene in near-real time to support tactical decision making.

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